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16. Abstract

The properties and applications of composite materials are reviewed. Glass, carbon, Kevlar, ceramic, whisker, and metal matrices are discussed. The quantitative distribution of high technology fibers in various applications is given. The role of aerospace industry in the development and promotion of composite utilization is duscussed. Consumption trends indicate a rapid development of the composite market.

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COMPOSITE REVIEW

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The composite materials market will explode over the next ten years. This is generally how reviews define the future of these materials. But will this forecast become a reality? What need does it satisfy? Are all means required for this explosion already in place? To answer these questions a panorama of this activity may be outlined with a market estimate for its confirmation. However, it is certain that if we look to the past from decade to decade, the growth of these materials is considerable in all socioeconomic sectors. The environment is changing. Furniture,homes, construction, transport, hobbies, industrial equipment, medicine, all of these sectors call on these materials and are changing their image.

In the past, composite materials were replacement materials or, in contrast, sophisticated materials considered by some to lack quality, or by others to be excessively expensive. Now they have become economically competitive. They are also new development tools borrowed by the high technology industry and supported by industrial productions with broader distribution, giving them a more just image of high quality and high performance at competitive prices.

Aeronautics is witnessing this growth: from their use for internal nonstructural layouts of airplanes and for missile and satellite structures, they are now used for stressed structures of airplanes and helicopters. Thus, these materials are leaving areas

of marginal interest to enter into competition with traditional materials.

Not Just Mechanical Properties

If we take a step backward, composite materials were made with glass fiber, the first industrial fiber with interesting mechanical properties, allowing a weight gain to be made over metallic, steel and aluminum structures because of its low density, and at low costs.

Fibers combined with thermosetting resins (polyester or epoxies) were used in a short fiber state or even better in a long fiber state oriented along stress directions using fabric, unidirectional layers or roving arranged using automatic equipment. Accordingly, the French DIAMANT booster received a second state at the beginning of the 1960's: a tank of several cubic meters under high pressure, made of composite material, glass fiber and epoxy resin by SUD AVIATION (now called Aerospatiale) using a winding fiber process. This technique made it possible to achieve a weight savings of over 30% versus a metallic solution.

Since then, more developments have been made, other fibers have made their appearance, with increased mechanical performance with respect to their density, but also with new properties.

The performance battle also resulted in cost gains.

For specific tension characteristics, growth was very quick: from glass to aramide (Kevlar) fiber, to carbon fiber - to what else? Other fibers are announced by different manufacturers, but due to the investment required, the potential interest of customers is tested. "Super Kevlar' or high performance polyethylene fibers or super carbon?

At Aerospatiale, these developments were of course followed to remain ahead. Casings of propulsion systems will be made of carbon

if performance is focussed on. However for other applications glass fiber is not dead. Price is an important factor, unless other stakes are given consideration.

It was due to the incentive of aircraft manufacturers, who demanded a creep fracture of 2% for a carbon fiber, that progress in specific strength was made. In contrast, the demand for low costs is the reason for the development of carbon fibers using other processes than polyacrylonitrile, such as pitch which the Japanese and Americans are trying to develop.

These fibers behave differently according to their nature, their diameter: some of electrical properties, others mechanical or thermal properties, such as pure silica fiber. The expected growth primarily concerns their operating temperature (at least 100° for a polyethylene fiber or up to 1100° with ceramic fibers - for motor mechanics 1400° would be necessary). Finally other methods could be used, monocrystals or trichites or even whiskers have mechanical properties that can exceed 10 Gpa with thermal strength up to 1500°C. A table can largely summarize these properties, while showing the diversity in the supply sources and the cost level (see table).

The Matrix

However a composite material is also a matrix which bonds fibers and shapes the object. Of the traditional matrices widely used as polyesters and epoxies, interest is now in new families like the polyimides, bismaleimides and other polystyrilpyredines. The objectives are still the same: increasing the mechanical, thermal performance, while reducing the costs of raw materials and above all of the transformation process. In this regard, thermoplastics could play an important role because they are prepared quickly and the real improvement they offer. PEEK steals the show in this regard, still for aeronautics and space; other matrices were studied, carbon in particular.

FIBERS		DENSITY	STRENGTH (Mla)	MODULUS (Mla)	EXPANSION	THERMAL CONDUCTIVTY (W/m° L)	TEMPERATURE ADMISSIBLE	PRICE/KG (FRANCS)
GLASS	E	2,60	2750	73000	5 10-6	1	500	10
	R	2,55	3650	86000	5 10-6	1	650	50
	S	2,50	3900	67000	5 10-6	1	700	80
CARBON	HR	1,80	4000	230000	- 0,1 10-6	10	350	400
	HM	1,90	2500	380000	- 0,5 10-6	100	350	1000
	THM	2,00	2000	500000	- 1 10-6	300	350	4000
ARAMIDE		1,44	3650	130000	- 2 10-6	0,05	160	250
CERAMIC	Alumina	3,90	1400	380000	7 10-6	20	1500	3000
	Silicon Carbide	2,55	2500	180000	3 10-6	60	1250	3500
	Silicon Nitride	3,20		250000	2,5 10-6	8	1700	3500
	Silica	2,20	1500	70000	0,5 10-6	1,5	1000	500
FUTURE POLYETHYLENE		0,96	3000	100000		0,3	150	50
SUPER KEVLAR		1,44	3900	130000	- 2 10-6	160		
WHISKERS	Silicon Carbide	3,20	21000	490000	4,5 10-6	40,40	3500	3500
	Silicon Nitride	3,20	14000	385000	2,5 10-6	30	1400	3500
REFERENCE METALS	Aluminum	2,8	500	70000	23 10-6			
	Steel	7,8	2000	110000	8,5 10-6			

Aerospatiale industrialized a carbon/carbon material with a very high thermomechanical performance in a neutral atmosphere (above 3000°).

Other materials are being studied, particularly ceramics, glass and metallic materials which would allow temperatures to be reconciled with the oxidizing medium. Applications already exist and could lead to a real technological revolution

MATRICES WITH PRICES AND TEMPERATURES
FOR MAXIMUM USE

POLYESTERS	100° C	10 F/KG
EPOXY	150° C	50 F/KG
POLYIMIDES	250° C	200 F/KG
PEEK THERMOPLASTICS	250° C	800 F/KG
CARBON	400° C (AIR)	10 F/KG (AIR)
CERAMICS	1500° - 2000° C	100 to 1000 F/KG
METALLIC MATRICES	500° C	250 F/KG

From raw materials to products other elements are missing from the chain: these are design methods, semi-products and transformation processes.

Design Methods

A composite material can be made, as we have seen, using a wide variety of metallic, organic or mineral raw materials, but combining a stiffener with another matrix should satisfy a certain number of criteria, the essential ones of these being:

The chemical and physical compatibility of materials in contact,

The performance levels (in terms of specifications) (mechanical, chemical, dimensional, electrical, thermal, appearance, etc.),

The preparation process based on the part geometry, its

sampling, and the series under consideration,

the quality assurance means,

the cost of ingredients,

the production and control costs.

Their use is therefore conditioned by the existence of design means.

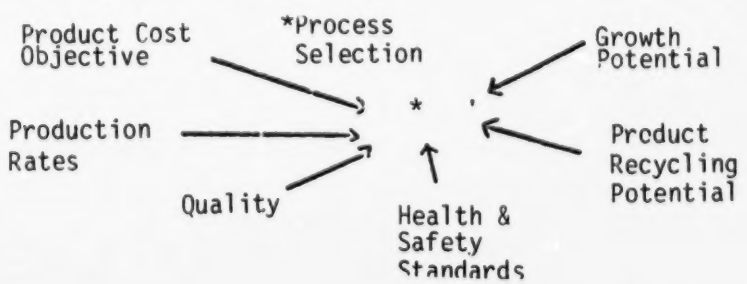
These means exist today; even if they still have to be supplemented to meet specific requirements. Thus data banks are available and simple or sophisticated computer means were developed over the years to allow the design to be integrated with computer aided fabrication, for some technologies.

Like many manufacturers, Aerospatiale has its own software to meet its specific needs, but more general methods are accessible.

In regard to fiber winding, the design-manufacturing integration is now complete. The control modulus of the machine is directly produced by computer. For other technologies, such as injection, models can be built and allow molds to be designed where material distribution is optimized. This is a problem that is difficult to solve with thermoplastics highly charged with fibers.

Semi-Products

The use of these materials is also related to their commercial presentation and to their degree of development. Organic matrix composites may be summarized below.



	Storage	Use
1) Fiber stiffener cut in bulk thread or roving on spool (roving for glass) all types of two- or three-dimensional types mixed fabrics sheet of short fibers braids		no special problem
2) Thermosetting resins thermoplastic	in a pot	a few hours
3) Preimpregnated thermosetting resins fibers or roving fabrics directional sheets sheet of short fibers braids compound	in a cold room	1 to several days
4) Preimpregnated thermosetting resins	no special conditions	no limitation
5) Semi-Products sections preimpregnated thick fabrics	-	-

Transformation Processes

Finally, the most important element for cost and quality control is the selection of the transformation process. From composites with a wide distribution to high performance composites, the problem is the same: to satisfy quality requirements and high production rates at minimum costs. To accomplish this all parameters which influence the selection should be taken into consideration.

A quick table may be drawn of conceivable processes.

Process	Material	Types of	Quality
Projection	Short fiber/polyester fiber	Large pieces	Low
Contact molding	VKC + polyester or epoxy fibers without pressure	Small complex serial pieces	depends on how carefully made
Compression molding SMC ZMC BMC	Preimpregnated	Large pieces without breaking down to small pieces	good
RIM injection molding	Preimpregnated	Small pieces	
	Short fibers and reactive organic compounds		
Automatic draping	Preimpregnated	All types	Reproducibility assured
Pultrusion Extrusion	Long organized fibers + resin	Long sections	Very good
Fiber winding	Roving whether preimpregnated or not	Pieces of similar shape	Reproducibility assured
Form weaving + impregnation	Dry or preimpregnated fibers	Pieces of simple shape revolving symmetry blocks	Very good

SMC Shit Molding compound
ZMC Billion Process
BMC Bulk molding compound
RIM Reaction injection molding

Automatic Processes At Aerospatiale

To ensure quality and reproducibility, as well as lower costs, Aerospatiale developed automation right from the beginning.

One process, fiber winding, perfectly adapted to revolving symmetry forms, but also to numerous hollow forms, provided that they do not have a rough surface, was particularly developed for its own needs.

The fibers ar arranged along a defined trajectory by computer. Optimization, reproducibility and quality are assured. They are applied to propulsion units but also to other objects such as high pressure gas storage tanks - where the strength function is taken over by the Kevlar or carbon glass composite, depending on the needs and on the sealing function using an internal elastometric or metallic casing.

Aerospatiale designed its machines, but today such machines are offered by manufacturers in a catalog. For highly refactory materials reinforced by carbon or ceramic fibers, Aerospatiale also developed special machines to weave pieces into form.

These substrates may then be impregnated with resin or carbon or even ceramic to meet the requirements For composites with very high mechanical and thermal performance, automation is necessary. All parameters are monitored by automatic means often designed "in-house", but always developed in conjunction with specialized forms. For other sectors of aeronautics, draping is a technology still used, but is aided more and more. Thus means were studied to automatically guide the operators and monitor the proper development of operations (optical sensors, man/machine dialogue) another phase will be passed with the draping robots that Aerospatiale and Dassault are jointly studying.

However it is easy to understand that each piece has its special features and therefore a different use.

The automobile industry is very familiar with this problem and is selecting in turn the SMC, ZMC, BMC processes according to the pieces used. This does not mean it is giving up the more sophisticated processes of aeronautics.

Fiber winding is used to produce transmission shafts.

Aerospatiale values its skill in offshore drilling by making tubes with resistance to an internal pressure of over 1800 bars.

The Market, the Future

We cannot give a complete list of applications which many specialized periodicals give. It may therefore be concluded with the help of a few figures indicating the percentages of the composite materials markets and the hopes that suppliers are putting at stake.

Carbon fiber consumption in t/year

1983	1984	1985	1986 forecasts
2250	2850	3700	4950

Distribution among the various activity sectors for 1983

Aeronautics & Spatial	Sports & Leisure	Industry	Total
800 (35%)	1050 (47%)	400 (18%)	2250

World production capacities of carbon fibers in January 1985

Japan	3000 tons/year
USA	2000 tons/year
EUROPE	1000 tons/year
TOTAL	6000 tons/year

Consumption of aramide fibers in t/year

198?	1984	1985	1986 forecast
5000	6200	7400	9000

Distribution by Activity Sector in 1984

AERONAUTICS	ARMOR-PLATING	PNEUMATICS	INDUSTRY	SPORTS	TOTAL
500 (8%)	3500 (56%)	1400 (23%)	100 (2%)	100 (2%)	6200

The glass fiber market is to be taken with more shaded because of the use of fibers for insulation, but if the high performance of market can be estimated to be 2000 tons/year, one must not forget the numerous uses they have in industry. The automobile alone used about 20,000 tons of glass fiber cut into 83. This figure doubled for 1985.

The growth prospects are even greater. Some vehicles are delivered with composite car body pieces. Shields are all now made of composite. The weight gain, the cost reduction and the elimination of corrosion are the main factors. In the aeronautics industry, the trend is the same.

The following diagrams show the expected short-term growth for airplanes and helicopters made by Aerospatiale. As for powder boosters, they are already 90% composite.

THERMOMECHANICAL MATERIALS
A LONG TRADITION AT AEROSPATIALE

Responsible for making heat shields for the reentry of ballistics systems of vehicles into the atmosphere. For many years Aerospatiale has been developing materials capable of resisting to higher temperatures as well the required production means. The requirements of its aeronautics and space programs encouraged it to study materials with higher and higher mechanical and thermal performance. The compromise necessary between strength, insulation and operating temperature thus gave birth to a range of initially organic, then carbon/carbon and finally carbon materials.

From Carbon to Ceramics

Carbon/carbon composite materials with stiffener made of carbon fibers combined by a carbon matrix are capable of supporting temperatures above 3000°C while preserving their mechanical properties.

Compared to the best graphites they have a three times higher resistance while having a much lower expansion ratio. Used for missiles and nozzles, they are the origin of the Aerolor line now available for numerous applications. However, for long operations at high temperatures and in a corrosive environment, the carbon is oxidizable. Ceramics, which has more strength than graphite, is more not very strong and it has a fragile type rupture. It is therefore natural that the technologies and methods used for composites were applied to ceramics to combine their high temperature strength with the ability to absorb local overstresses and a higher rupture energy.

Associated with the performance of raw materials and fibers in particular, these materials have not yet given all of their capabilities, but it is already conceivable to make them "stress", for some up to 1400°C, with a mechanical strength of the order of 400 m/a and above all a much higher creep fracture than that of massive ceramics.

Applications

Applications are being developed and some have already flown, such as radioelectric windows resistant at the very high temperatures of atmospheric reentry, thanks to the all silica composite material, insensitive to thermal shock.

Moreover, their low expansion associated with a good insulating power and high heat strength make these materials useful in turbine or Diesel motor applications. Cooperative efforts with the support of public authorities are pledged with engine manufacturers.

Finally, Hermes, spacecraft of the next decade will call on these materials for its thermal protections. The materials developed by Aerospatiale* are candidates.

Alain HORDONNEAU

*Cooperation with ceramics and composites.